CONFIDENTIAL

WEIL, GATES, BANNER & KUHL

FLIGHT EXPERIENCE OF INERTIA COUPLING IN ROLLING MANEUVERS

By Joseph Weil, Ordway B. Gates, Jr., Richard D. Banner, and Albert E. Kuhl

NACA High-Speed Flight Station

and

Langley Aeronautical Laboratory

SUMMARY

Violent coupled lateral-longitudinal motions have been encountered in flight on two airplanes during abrupt aileron rolls at relatively high speed. During these motions, various structural design loads and load factors were either exceeded or approached. It was demonstrated on one airplane that the motions can be approximated reasonably well by using a five-degree-of-freedom analysis.

From flight tests of the swept-wing airplane at relatively high altitude, it was found that the severity of the divergent tendency increased with roll velocity and was sensitive to roll direction and stabilizer input. Calculated results indicated that considerably more critical conditions from the loads standpoint can be expected at lower altitudes when the roll is initiated from a pull-up condition.

Perhaps one of the fundamental reasons for the occurrence of the large motions on both airplanes was the presence of insufficient directional stability. Doubling the directional stability level of the swept-wing airplane resulted in substantially improved flight characteristics; but calculations indicated that, if the tail size is increased beyond a certain point, considerably higher tail loads and larger peak normal accelerations can be obtained than with a tail affording a somewhat lower level of stability.

At present, analytical investigations are under way to enable a better understanding of the overall problem of coupled lateral-longitudinal motions in rolling maneuvers. It is not yet known whether a practical design approach exists that would produce desirable characteristics for a large range of flight conditions without the sacrifice of performance or the resort to artificial stabilization. It is also true that coupling can have a large effect on the predicted loads, even for configurations that have satisfactory handling qualities; therefore, the coupling of the lateral and longitudinal degrees of freedom should be considered for load evaluations of rolling maneuv[redacted]gh-speed airplanes.

[redacted]

INTRODUCTION

There is a deterioration in the static directional stability of many contemporary designs at the higher angles of attack and sideslip, and also with increase in supersonic Mach number, that can and have produced violent motions in flight.

Recently at the NACA High-Speed Flight Station, some rather violent coupled lateral-longitudinal motions have been experienced during abrupt aileron rolls on several airplanes in which a level of directional stability was present that would probably have been deemed acceptable for previous airplanes. Because this flight experience should be of considerable general interest to the loads engineer, inasmuch as it obviously affects the determination of design loads, it is believed timely to review briefly the problem and indicate some of the factors affecting its severity.

SYMBOLS

A	aspect ratio
a_n	normal acceleration
a_t	transverse acceleration
C_{n_β}	directional stability parameter
H_p	pressure altitude
I_X, I_Y, I_Z	moments of inertia about X-, Y-, and Z-axes, respectively
i_t	stabilizer deflection
L_V	shear load on vertical tail, radians/sec
M	Mach number
p_{max}	maximum roll velocity
t	time, sec
α	angle of attack, deg
β	angle of sideslip, deg
δ_{a_t}	total aileron deflection
δ_r	rudder deflection

[redacted]

[redacted]

$\Lambda_{c/4}$ angle of sweep measured at 0.25 chord, deg

$\Lambda_{\frac{3}{4}c}$ angle of sweep measured from 0.75 chord, deg

$\Delta\phi$ incremental bank angle

DISCUSSION

The basic outlines of the two airplanes discussed in this paper are shown in figure 1. One airplane had 45° sweepback; the other was essentially unswept. It can be seen from the moment-of-inertia ratios that these airplanes were rather heavily loaded along the fuselage, and such inertia characteristics can appreciably lower the roll rate at which large coupled motions might be encountered as indicated in reference 1.

The results of a time history of an abrupt two-thirds aileron roll to the left made on the swept-wing airplane from level flight at a Mach number of 0.70 and altitude of 32,000 feet are presented in figures 2 and 3. Soon after the aileron-control input, there is a steady decrease in angle of attack and development of negative (adverse) sideslip. (See fig. 2.) Between 3 and 4 seconds, the rates of divergence in angles of attack and sideslip increased markedly and the maneuver became uncontrollable. Recovery was made when the controls were brought close to their initial settings. During the motion, a left sideslip angle of 26° was recorded and angles of attack much larger than -16° were attained followed by 12° at recovery.

In order to determine the mechanism of this type of coupled lateral-longitudinal motion (including the effects of changes in the various derivatives), a five-degree-of-freedom analysis was made using an analogue computer. It is seen that the basic character of the motion is predicted fairly well. In order to illustrate the powerful effect of the coupling between the longitudinal and lateral modes of the motion, the sideslip estimated by the usual three-degree-of-freedom lateral equations and the angle of attack estimated by a two-degree-of-freedom analysis are also included. Although the initial sideslip motion is seen to be the same for the two methods, the three-degree-of-freedom method reaches a peak of only about $\beta = -5°$. The angle-of-attack comparison is even more revealing in that the stabilizer input of the pilot would have resulted in a large positive angle-of-attack change from a purely longitudinal analysis as opposed to the negative divergence shown by flight and the more refined analysis. The complexity of the problem can be further illustrated by the fact that calculations indicated that the indirect effect of the stabilizer input actually aggravated the sideslip and angle-of-attack divergence appreciably.

A normal acceleration of [illegible]g was recorded and about [illegible]0 percent of the design vertical-tail load attained. (See fig. 3.) The low dynamic pressure at which the maneuver was made saved the airplane from possible structural damage.

The question naturally arises whether such violent behavior could be expected at higher dynamic pressure where, from the loads standpoint, more critical conditions might be reached. An analogue computer has been used to study this question. Figure 4 summarizes the results of many of these calculations presenting the maximum estimated vertical-tail shear load as a function of the maximum rolling velocity attained in 360° left rolls. The dashed line represents data for a condition similar to that shown in figures 2 and 3 - an altitude of 32,000 feet and an initial 1 g condition. The solid lines show results for rolls made at 10,000 feet from initial conditions of 1 g and 2.5g. It was found from the calculations that 1 g rolls made at the lower altitude so greatly reduced the sideslip angles that, even if the 2.5 fold increase in dynamic pressure is considered, the tail loads for the most rapid rolls never approach the loads attainable at the higher altitude at somewhat lower rolling velocities. When the rolls were made at 10,000 feet from an initial 2.5g pull-up condition, however (the initial angle of attack being maintained at the higher altitude level), much larger tail loads were estimated at high roll velocities than for the higher altitude condition.

In order to study the effect of increasing the directional stability on the rolling characteristics, flight tests were made with two enlarged vertical tails. Figure 5 shows a sketch of the small and enlarged tails. Also shown is the variation of C_{n_β} with Mach number measured in flight. The largest tail (tail C) roughly doubled the directional stability of the small tail [illegible] of the Mach number range.

The effect of increasing tail size on the characteristics in abrupt left rudder-fixed aileron rolls at an average Mach number of 0.70 and altitude of about 31,000 feet are shown in figure 6. Presented are the maximum change in sideslip angle and the maximum change in angle of attack at the first peak plotted against the maximum roll rate attained in a maneuver. The first roll made for this flight condition (using tail A) resulted in the violent maneuver previously discussed and is approximately located in figure 6 by the circle. The remainder of the data obtained with tail A was restricted to small aileron deflections and bank angles of the order of 45° to 60°. The data for the larger tails represent 360° rolls. If a calculated curve for 360° rolls with tail A is used (as a guide in lieu of flight data), it is seen from the sideslip data that increasing the tail size delayed somewhat the roll velocity at which $\Delta\beta$ increases much more rapidly with further increase in roll rate. Also, for the largest tail there appears to be a substantial decrease in the divergent tendency at high roll rates. The five-degree-of-freedom calculations show good agreement for the tail A data at small bank angles and illustrate the large effect of the duration of the maneuver on the characteristics at higher roll velocities.

From the lower portion of figure 6, it can be seen that the initial negative change in angle of attack was relatively small for the larger tails, never approaching the divergent tendencies of the original maneuver. It should be mentioned, however, that the positive change in angle of attack in recovery was often somewhat larger than the first peak with tail C.

The results of figure 6 indicate that doubling the level of the directional stability greatly improved the overall characteristics, and one might wonder how further large increases in the size of the vertical tail would affect the results. Figure 7 presents the results of time histories calculated for directional stability levels of $0.001C_{n_\beta}$, $0.002C_{n_\beta}$, and $0.004C_{n_\beta}$ per degree for a roll velocity of about -3.0 radians/sec. The sideslip data show the large reduction in β when C_{n_β} is increased from 0.001 to 0.002. When C_{n_β} is again doubled, however, the sideslip angle developed is only slightly reduced and the maximum tail load would be much larger because of the increased tail area required.

It should also be noted that, although the initial angle-of-attack change is practically nil for the largest tail, the peak positive angle on recovery is almost as large as that with the smallest tail. (See fig. 7.)

The results of figure 7 indicate the possibility of an optimum tail size from the loads standpoint for a given flight condition and further illustrate the complexity of the overall problem.

The effect of Mach number and roll direction on the maximum sideslip angle developed in flight in abrupt 360° rolls is presented in figure 8 for the largest tail (tail C). In order to clarify the comparison, $\Delta\beta$ is plotted for left rolls shown by solid lines and $-\Delta\beta$ for right rolls shown by dashed lines. It is seen that "adverse" sideslip is present in the subsonic maneuvers and "favorable" sideslip at M = 1.25. A very interesting point is the much greater sideslip attained in the left roll than in corresponding right rolls at the higher roll velocities. This roll-direction effect is directly attributable to engine gyroscopic effects and is in general agreement with calculated results. At M = 1.25, the right rolls developed slightly greater maximum sideslip angles than left rolls. Although there was no adverse pilot comment on the supersonic rolls, the sideslip angle attained of almost 6° exceeded the temporary limit by 1°.

[redacted]

The time history of an abrupt aileron roll made at a Mach number of 1.05 on the unswept airplane at an altitude of 30,000 feet is shown in figures 9 and 10. The level of directional stability for this maneuver was about $C_{n_\beta} = 0.0038$ per degree. In this maneuver, favorable sideslip builds up rapidly with rolling velocity; however, no large change in α occurs until a sideslip angle of almost 20° is reached ($t = 4$ seconds) at which time the angle of attack abruptly decreases to -11°. (See fig. 9.) The pilot applied considerable up-stabilizer control to stop the pitch-down tendency and this possibly contributed somewhat to the 19° angle of attack reached when the airplane pitched up. When the rolling motion stopped, the airplane quickly recovered.

The violence of this maneuver can best be appreciated from the fact that the load factor reached -6.7g at $t = 4.5$ seconds and then reached 7.0g less than 1/2 second later. (See fig. 10.) A lateral acceleration of -2g, pitching accelerations as high as 8 radians/sec^2, and a vertical-tail shear load approximately 50 percent of design were also measured.

As in the case of the violent maneuver experienced with the swept-wing airplane, one of the fundamental causes of this maneuver on the unswept airplane is believed to be a deficiency in directional stability in conjunction with mass distributed primarily along the fuselage. The statement concerning the lack of directional stability might seem contradictory inasmuch as the value of C_{n_β} for this airplane was about three to four times the value for the swept-wing airplane with the small tail. However, the value of the derivative C_{n_β} can be misleading because of relatively small wing size. When the two airplanes are compared by using the more rational lateral period, for example, the unswept airplane has a directional stiffness approximating the original swept-wing airplane.

CONCLUDING REMARKS

In conclusion, it has been shown that violent coupled lateral-longitudinal motions have been encountered in flight on two airplanes during abrupt aileron rolls at relatively high speed. During these motions, various structural design loads and load factors were either exceeded or approached. It was demonstrated on one airplane that the motions can be approximated reasonably well by using a five-degree-of-freedom analysis.

From flight tests of the swept-wing airplane at relatively high altitude, it was found that the severity of the divergent tendency increased with roll velocity and was sensitive to roll direction and

[redacted]

stabilizer input. Calculated results indicated that considerably more critical conditions from the loads standpoint can be expected at lower altitudes when the roll is initiated from a pull-up condition.

Perhaps one of the fundamental reasons for the occurrence of the large motions on both airplanes was the presence of insufficient directional stability. Doubling the directional stability level of the swept-wing airplane resulted in substantially improved flight characteristics; but calculations indicated that, if the tail size is increased beyond a certain point, considerably higher tail loads and larger peak normal accelerations can be obtained than with a tail affording a somewhat lower level of stability.

At present, analytical investigations are under way to enable a better understanding of the overall problem of coupled lateral-longitudinal motions in rolling maneuvers. It is not yet known whether a practical design approach exists that would produce desirable characteristics for a large range of flight conditions without the sacrifice of performance or the resort to artificial stabilization. It is also true that coupling can have a large effect on the predicted loads, even for configurations that have satisfactory handling qualities; therefore, the coupling of the lateral and longitudinal degrees of freedom should be considered for load evaluations of rolling maneuvers on most high-speed airplanes.

REFERENCES

1. Zimmerman, Charles H.: Recent Stability and Aerodynamic Problems and Their Implications as to Load Estimation. (Prospective NACA paper.)

CHARACTERISTICS OF AIRPLANES

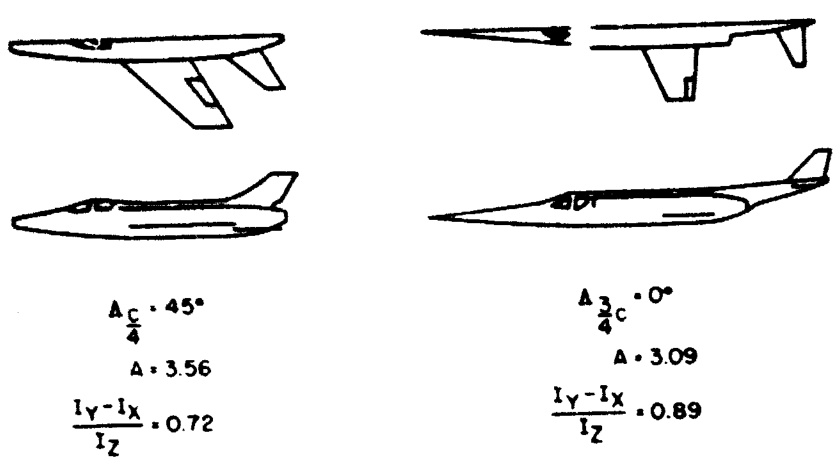

Figure 1

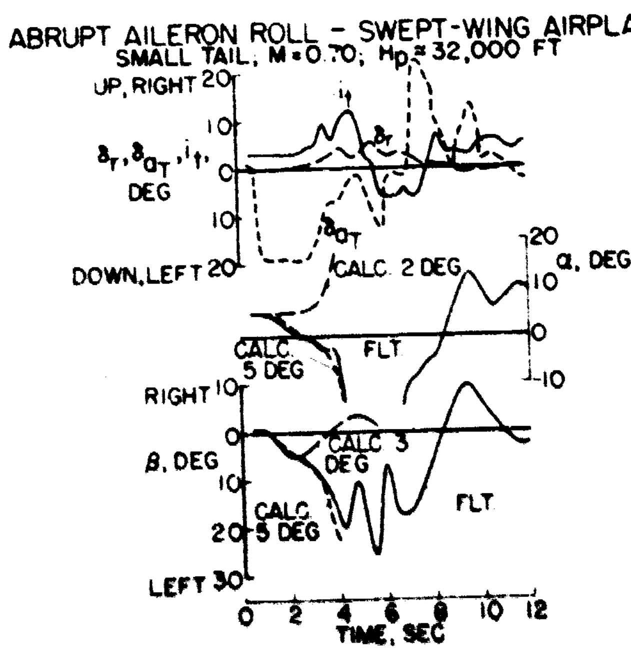

Figure 2

[redacted]

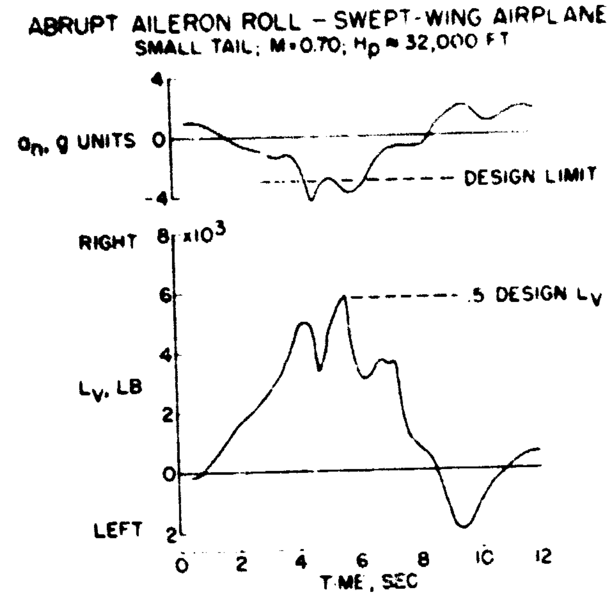

Figure 3

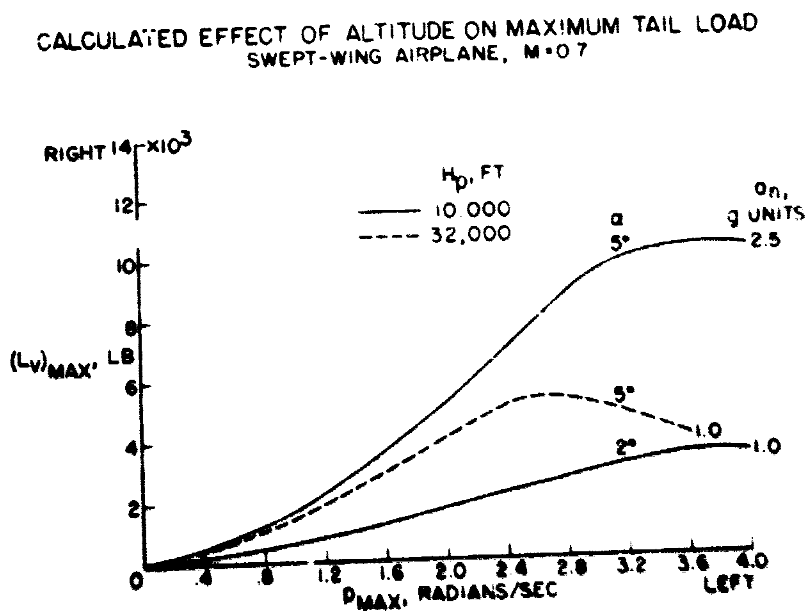

Figure 4

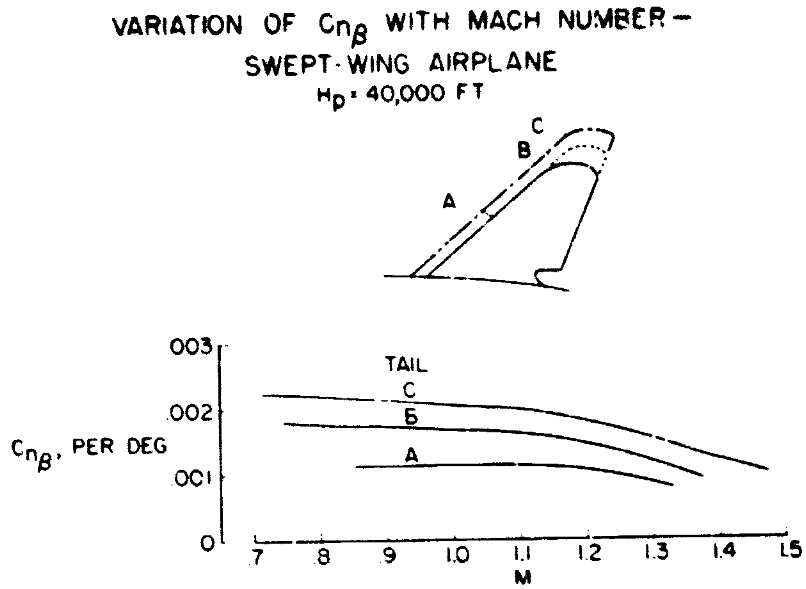

Figure 5

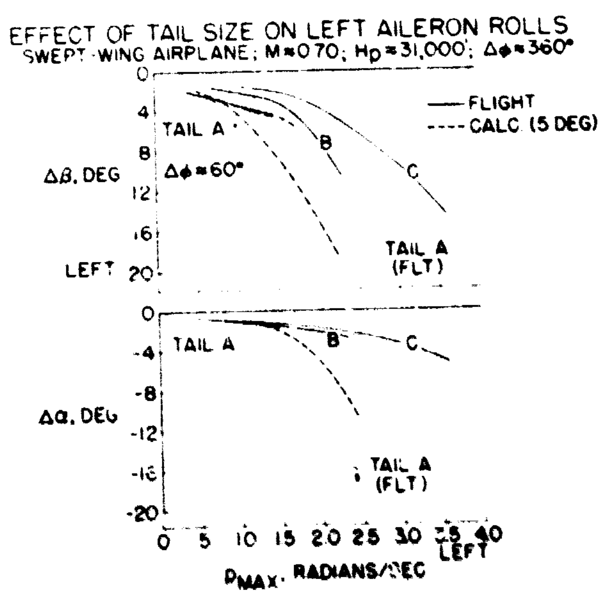

Figure 6

CALCULATED EFFECT OF C_{n_β} ON ROLLING MOTION - SWEPT-WING AIRPLANE
$\Delta\phi \approx 360°$; $p_{MAX} \approx -3$ RADIANS/SEC

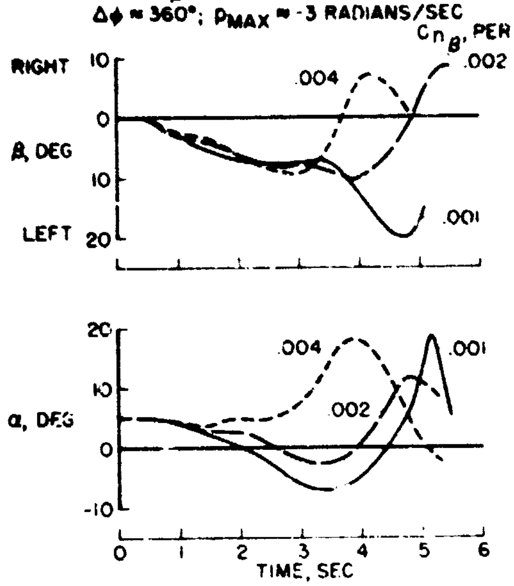

Figure 7

EFFECT OF ROLL DIRECTION ON $\Delta\beta$ AT SEVERAL MACH NOS.
TAIL C; SWEPT-WING AIRPLANE; $\Delta\phi \approx 360°$

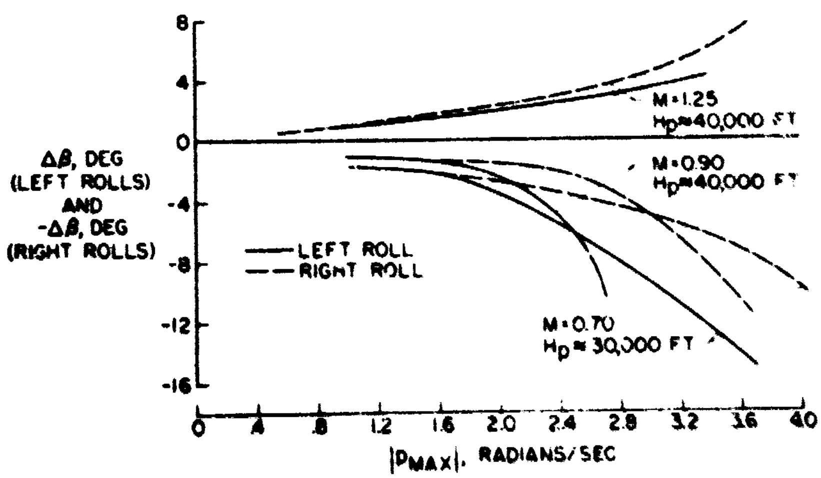

Figure 8

ABRUPT AILERON ROLL - UNSWEPT AIRPLANE

M=1.05; Hp=30,000 FT

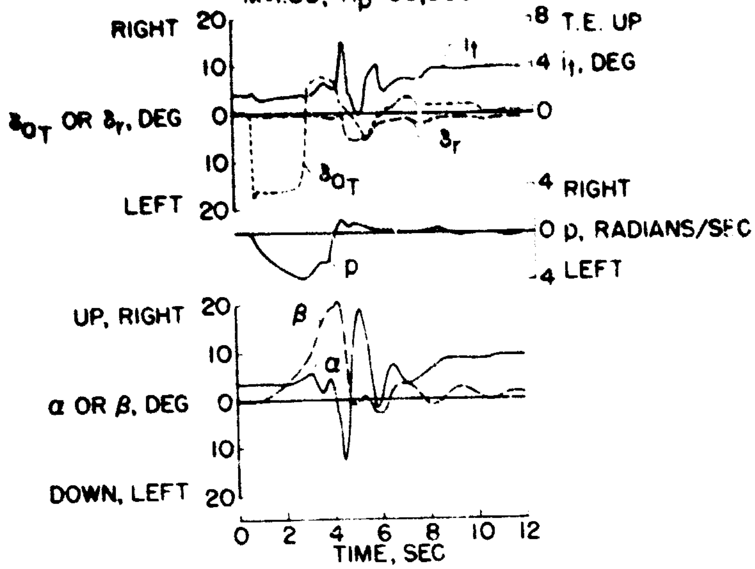

Figure 9

ABRUPT AILERON ROLL - UNSWEPT AIRPLANE

M=1.05, Hp=30,000 FT